11.1

Contrasting vertical structures of the stable boundary layer

L. Mahrt* and Dean Vickers
Oregon State University, Corvallis, OR

1. INTRODUCTION

Wyngaard (1973) introduced the concept of *z-less stratification* for cases where the stratification is sufficiently strong, that the turbulence no longer is in significant communication with the surface (see also Holtslag and Nieuwstadt, 1986). Then z is no longer a primary scaling variable, nor is the boundary-layer depth. The eddies are vertically constrained by strong stratification. However, the z-less concept implies more than small eddies, since vertically continuous turbulence can still organize according to z even if the eddies at any level are small compared to z. For example, with *local similarity* where the relevant Obukhov length must be recast in terms of local fluxes at level z instead of surface fluxes (Nieuwstadt, 1984), the overall vertical structure is still posed in terms of z/h even if the eddy size is small compared to z. In this sense, local similarity still satisfies the criteria for traditional boundary layers. On the other hand, continuous turbulence between the surface and level z might still qualify as primarily z-less turbulence if the principal source of turbulence is detached from the surface and the distance above the ground surface is only a secondary influence.

A clear example of z-less turbulence is layers of turbulence separated by nonturbulent layer(s). This vertical structure does not satisfy the traditional concept of a boundary layer in that surface-based processes are of secondary importance (Mahrt, 1999). Well-defined laboratory examples of such "upside-down" boundary layers can be found in Ohya (2001). In this study, the boundary layer is upside down if turbulence increases with height and the transport of turbulence energy is downward toward the surface. While the upside-down boundary layer may often satisfy the conditions for z-less turbulence, the definitions are not equivalent in that the upside-down class requires downward transport of turbulence energy.

2. DATA

The primary data set is 6 levels of sonic anemometer data from the 60-m tower in CASES99 (Poulos et al., 2001; Sun et al, 2002), for the month of October, 1999 over relatively flat grassland. In addition, we include data from the 1.5-m and 5-m levels of a mini tower, 10 m to the side of the main tower. The sonic anemometer at 1.5 m was moved to the 0.5-m level on 19 October but still included in the study.

The data was quality controlled following Vickers and Mahrt (1997). Perturbations are defined as deviations from a stability-dependent averaging window and covariances are averaged over one hour to reduce flux sampling errors. Mostly cloudy cases were removed by discarding 8 out of the 107 hourly records where the magnitude of the surface net radiation loss was less than 40 Wm^{-2}.

To compute mean wind profiles, we have used the R.M. Young propeller anemometer and wind vane data for 15 m and above and the sonic anemometers at 5 and 1.5 m (Figure 1). The profile of the Richardson number was calculated by fitting the height dependence of wind speed and potential temperature to a log-linear profile and then evaluating the gradients analytically. This Richardson number neglects directional shear, which was sometimes important near the surface.

Vertical transport of kinetic energy is represented by the vertical transport of vertical velocity variance. The vertical transport of the horizontal velocity variances behaved in a similar manner but is more sensitive to the choice of averaging time and to random flux errors.

3. VERTICAL STRUCTURES

The turbulence energy may: 1) decrease with height across the tower layer, as in a thin traditional shallow boundary layer, 2) vary slowly with height, as in a boundary layer that is much deeper than the tower, or 3) increase with height in cases where the turbulence is generated at higher levels (upside-down boundary layer). To separately study the vertical structure of these states, we composite the structure of the turbulence according to classes based on the ratio of σ_w at 55 m to that at 5 m. The data consists of 107 one-hour records between 1900 and 0600 local standard time where the data is available for all eight sonic anemometers. Eight records were eliminated where the net radiative cooling was less than 40 Wm^{-2}, presumably due to clouds. The class where the turbulence increases with height is defined as that

**corresponding author address:* L. Mahrt, College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR, 97331, USA; *email:* mahrt@coas.oregonstate.edu

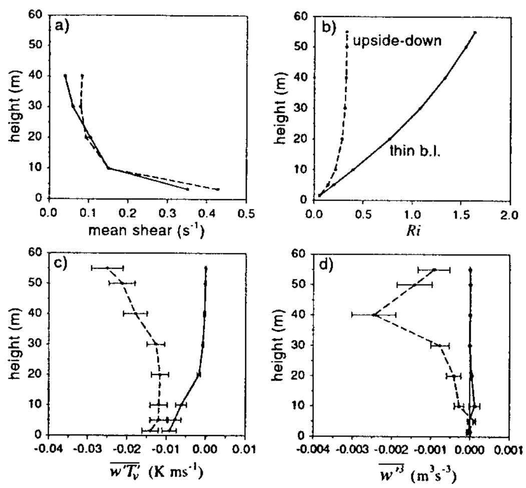

Figure 1: The composited vertical structure of the a) mean shear, b) local gradient Richardson number, c) virtual heat flux and d) $\overline{w'^3}$, for the class of thin traditional boundary layers (solid lines) and the upside-down class (broken lines)

where the ratio exceeds 1.5, which captures 26 one-hour records. The thin traditional boundary layer where the turbulence decreases with height will be defined as cases where the ratio is less than 0.6, which captures 21 one-hour records. The intermediate class corresponds to the case where the turbulence varies slowly with height and could be associated with a boundary layer that is much deeper than the tower. For the intermediate class, the tower is not tall enough to capture a significant fraction of the boundary layer and the turbulence quantities do not vary substantially across the tower layer. This class also includes some cases of poorly defined vertical structure. This intermediate class includes 52 one-hour records. We concentrate on the vertical structure of the thin boundary layer and the upside-down class (Figure 1).

The thin traditional boundary layer resolved by the tower can occur any time during the night but most often occurs in the early evening with very stable conditions where $z/L > 1$ near the surface. The magnitude of the downward heat flux in the composited thin boundary layer decreases linearly with height to approximately 30 m and then is small above this level. For the thin traditional boundary layer, the mean shear decreases monotonically with height (Figure 1a). For the upside-down class, the mean shear decreases significantly with height only up to 20 m and increases slightly above 30 m becoming twice as large as that for the thin traditional boundary layer at the 40-m level. For individual cases, the local shear in the upper part of the tower layer may be locally large but the level of the significant shear varies between cases, and does not occur at any level for some cases. Therefore, the composited shear profile does not show any well-defined shear maximum.

The greater shear for the upside-down class at higher levels exerts a strong influence on the Richardson number at these levels, partly because the Richardson number depends quadratically on the shear and partly because the stratification decreases rapidly with height (not shown). The Richardson number increases with height within and above the thin traditional boundary layer (Figure 1b), although the Richardson number profile is sensitive to the method of calculation. For the upside-down class, the Richardson number does not increase with height above 30 m, in contrast to the traditional thin boundary layer. While the buoyancy flux decreases to immeasurably small values above 30 m for the thin traditional boundary layer, the magnitude of the buoyancy flux increases above 30 m for the upside-down class. The vertical structure of the stress (not shown) is similar to that of the buoyancy flux but slightly less organized.

For the thin traditional boundary layer, the vertical transport of vertical velocity variance is near zero or weak upward (Figure 1d). Since the length scale of the turbulence is small for strongly stratified boundary layers with weak turbulence, the turbulence is more efficiently dissipated locally. The downward transport of the vertical velocity variance for the upside-down class (Figure 1d) implies that this class is not simply a boundary layer which is much deeper than the tower layer, but contains turbulence associated with shear-generation that is not directly coupled to the surface. This is not a traditional boundary layer.

4. MIXING LENGTH

Because boundary-layer depths are often 20 m or less, the surface-layer prediction of the mixing length, $\kappa z/\phi_m$ is often expected to be valid at night only in the lowest few metres. The failure of similarity theory at higher levels is supported by the composited diurnal variation of the aerodynamic roughness length (Figure 2). The roughness length was computed using Monin-Obukhov similarity theory and the observed heat and momentum fluxes. At 1.5 m, the roughness length is approximately independent of time of day. However, for the 5- and 10-m levels, the aerodynamic roughness length dramatically decreases at night. Since the physical roughness of the surface does not change, this variation is due to inapplicability of surface layer similarity theory. As a consequence, the study of the surface layer similarity theory requires eddy correlation measurements within the lowest few metres. Note that the thermal roughness length based on the surface radiation temperature varies sub-

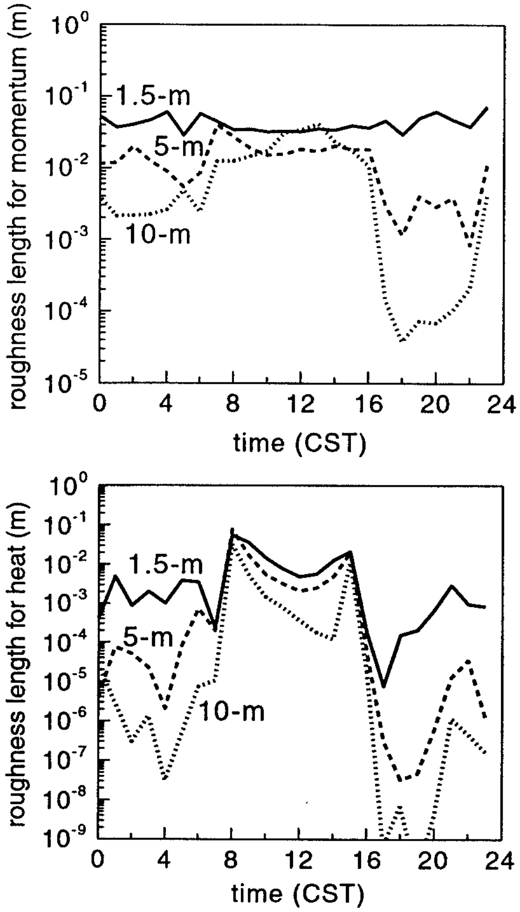

Figure 2: The dependence of the composited roughness length on time of day for the 1.5- 5- and 10-m levels.

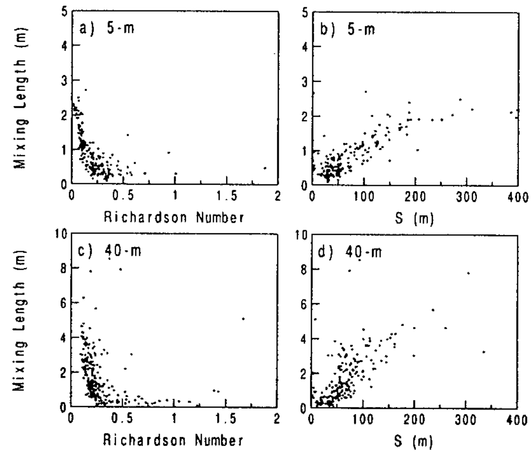

Figure 3: The dependence of the mixing length on the layer Richardson number centered about the eddy correlation level and the dependence of the mixing length on the bulk length scale (Eq. 2) for the 5- and 40-m levels.

stantially even at 1.5 m over this simple surface.

However, formulating the mixing length in terms of $\kappa z/\phi_m$ based on local fluxes at level z provides a credible approximation to the mixing length even above the surface layer up to about 40 m. Above 40 m, this approximation overestimates the mixing length. Part of the success above the surface is that this approximation becomes approximately z-less for strong stabiiity (Mahrt, 1999). However, part of the success is due to self correlation in that both the mixing length and $\kappa z/\phi_m$ are proportional to u_*.

Dismissing similarity theory for all but the lowest tower level, we now explore the relationship between the mixing length and the gradient Richardson number (Figure 3). Here we focus on the 5-m level, which is almost always within the boundary layer, and the 40-m level, which is generally above the boundary layer except during strong mixing periods. Several features transcend the behavior of the mixing length at all of the levels, whether it is within the boundary layer or above it. The mixing length decreases sharply from near-neutral conditions ($Ri \approx 0$) to modestly stable conditions ($Ri \approx 0.20$). The relationship is rather successful considering large random flux errors and difficulties of estimating mean vertical gradients.

For stronger stability ($Ri > 0.20$), the value of the mixing length tends to remain constant with large scatter. Surprisingly, eliminating cases with large intermittency, nonstationarity and downward transport of turbulence energy does not visibly reduce the scatter. The intermittency is smallest near the surface and increases with height.

Near-neutral conditions include numerous cases of significant nonstationarity. These cases are associated with transition periods where the flow changes between unstable and stable or between stable and unstable. Nonetheless, the value of the observed mixing length at neutral conditions is consistent with the asymptotic trends of the stability dependence for the stable and unstable regimes. The near-neutral value of the mixing length increases with height up to about 20 m and then becomes approximately constant with height with a value of 6 m. The boundary-layer depth does not influence the height dependence of the neutral mixing length for the composited profiles in an obvious way possibly because the boundary-layer depth varies substantially between the different records and is not well defined for many cases.

To model the z-less mixing length, we pursue a simple

dependence on the Richardson number

$$l(z) = l_0(z)exp(-aRi) + b \tag{1}$$

The principal closure problem is specification of the mixing length at neutral stability, l_0. For the present data, $l_0 = 6m$ is an adequate approximation but the generality of this value is not known and the specification of a dimensional quantity is unappealing.

4.1 Alternative formulation

The principal disadvantage of Eq. 1 is specification of the asymptotic value at neutral stability. This difficulty can be avoided by formulating the mixing length as

$$S(z) = C(z)\frac{(\Delta U)^2}{(g/\Theta)\Delta\Theta} \tag{2}$$

where $C(z)$ is a nondimensional coefficient. This relationship explains a substantial fraction of the variance of the mixing length and contains no self correlation. The coefficient $C(z)$ increases with height and asymptotes to a roughly height-independent value of 2.5 x 10^{-2}. The disadvantage of this approach is that it asymptotes to infinity at neutral conditions where $\Delta\Theta$ vanishes, at least for a fixed Δz. However, with increasing mixing length, the relevant temperature difference needs to be computed over larger scales corresponding to the eddy size, in such a manner that $\Delta\Theta$ recognizes the stratification at the edges of the mixing layer, or, becomes constrained by the ground surface.

During the oral presentation, several different models which combine surface layer similarity theory and the above z-less relationship will be evaluated.

5. ACKNOWLEDGMENTS

We gratefully acknowledge the field assistance of Jielun Sun and Sean Burns, who also provided the thermocouple data. We also gratefully acknowledge the field assistance of the ATD staff from the National Center for Atmospheric Research. This material is based upon work supported by Grant DAAD19-9910249 from the Army Research Office and Grant 0107617-ATM from the Physical Meteorology Program of the National Sciences Program.

REFERENCES

Holtslag, A. A. M. and Nieuwstadt, F. T. M.: 1986: Scaling the atmospheric boundary layer. *Boundary-Layer Meteorol.*, **36**, 201-209.

Mahrt, L., 1999: Stratified atmospheric boundary layers. *Boundary-Layer Meteorol.* **90**, 375-396.

Nieuwstadt, F. T. M., 1984: The turbulent structure of the stable, nocturnal boundary layer. *J. Atmos. Sci.*, **41**, 2202-2216.

Ohya, Y., 2001: Wind-tunnel study of atmospheric stable boundary layers over a rough surface. *Boundary-Layer Meteorol.*, **98**, 57-82.

Poulos, G. S., W. Blumen, D. Fritts, J. Lundquist, J. Sun, S. Burns, C. Nappo, R. Banta, R. Newsome, J. Cuxart, E. Terradellas, B. Balsley, M. Jensen, 2001: CASES-99: A comprehensive investigation of the stable nocturnal boundary layer. *Bull. Amer. Meteor. Soc.*, in press.

Sun, J., Lenschow, D., Burns, S., Coulter, R., Wesely, M., Nappo, C., Cook, D., Banta, R., Newsom, R., Balsely, B., Jensen, M., Lee, X., and Hu, X.-Z.: 2002, 'Intermittent turbulence in stable boundary layers and its relationship to weather disturbances. *Boundary-Layer Meteorol.* to appear.

Vickers, D. and Mahrt, L.: 1997: Quality control and flux sampling problems for tower and aircraft data. *J. Atm. and Oc. Tech.*, **14**, 512-526.

Vickers, D. and Mahrt, L.: 2002: Stability dependent averaging length for estimating fluxes. This volume.

Wyngaard, J.C., 1973: On surface-layer turbulence. Workshop on Micrometeorology, D. A. Haugen, Ed., Boston, Amer. Meteor. Soc., 101-149.